NREL
Transforming ENERGY

Integrating Ultra-high Levels of Variable Renewable Energy into Electric Power Systems

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NREL - Driving innovation in Power Systems Engineering

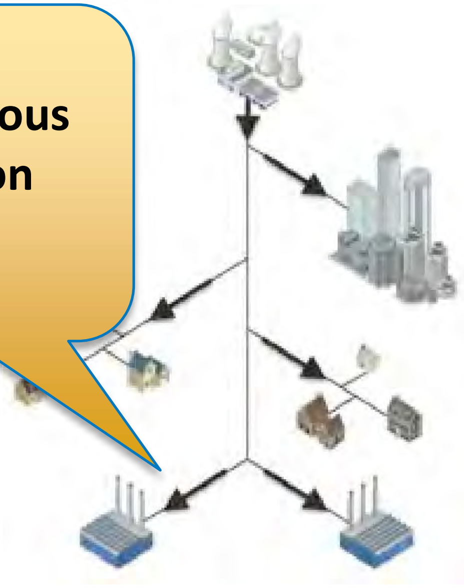
Outline

- Understanding current and future power systems
- Current state of variable renewable energy (VRE): solar and wind
- Current power systems operating with VRE
- Challenges and solutions of operating power systems with very high levels of VRE
- Research needs

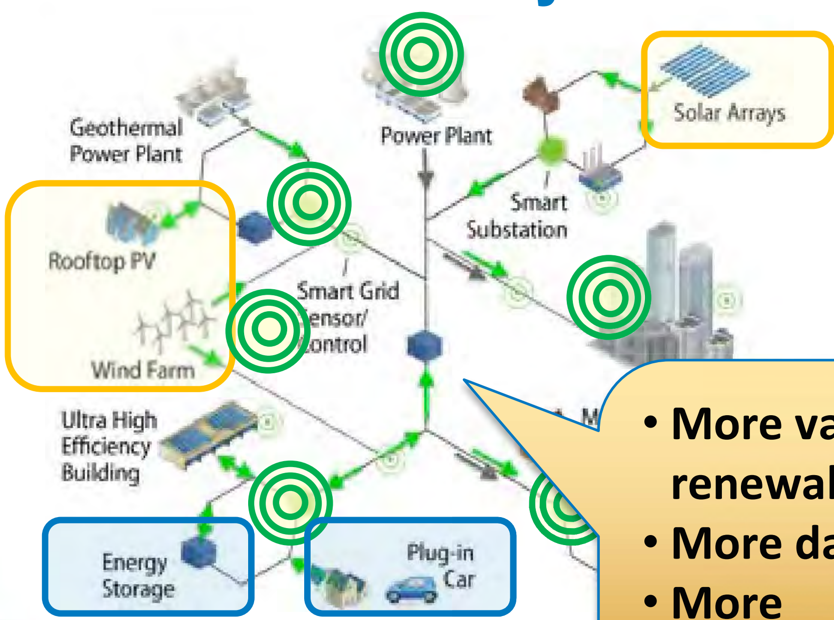
Evolution of the Power System

Current Power System

- Large synchronous generation
- Central control.



Future Power Systems

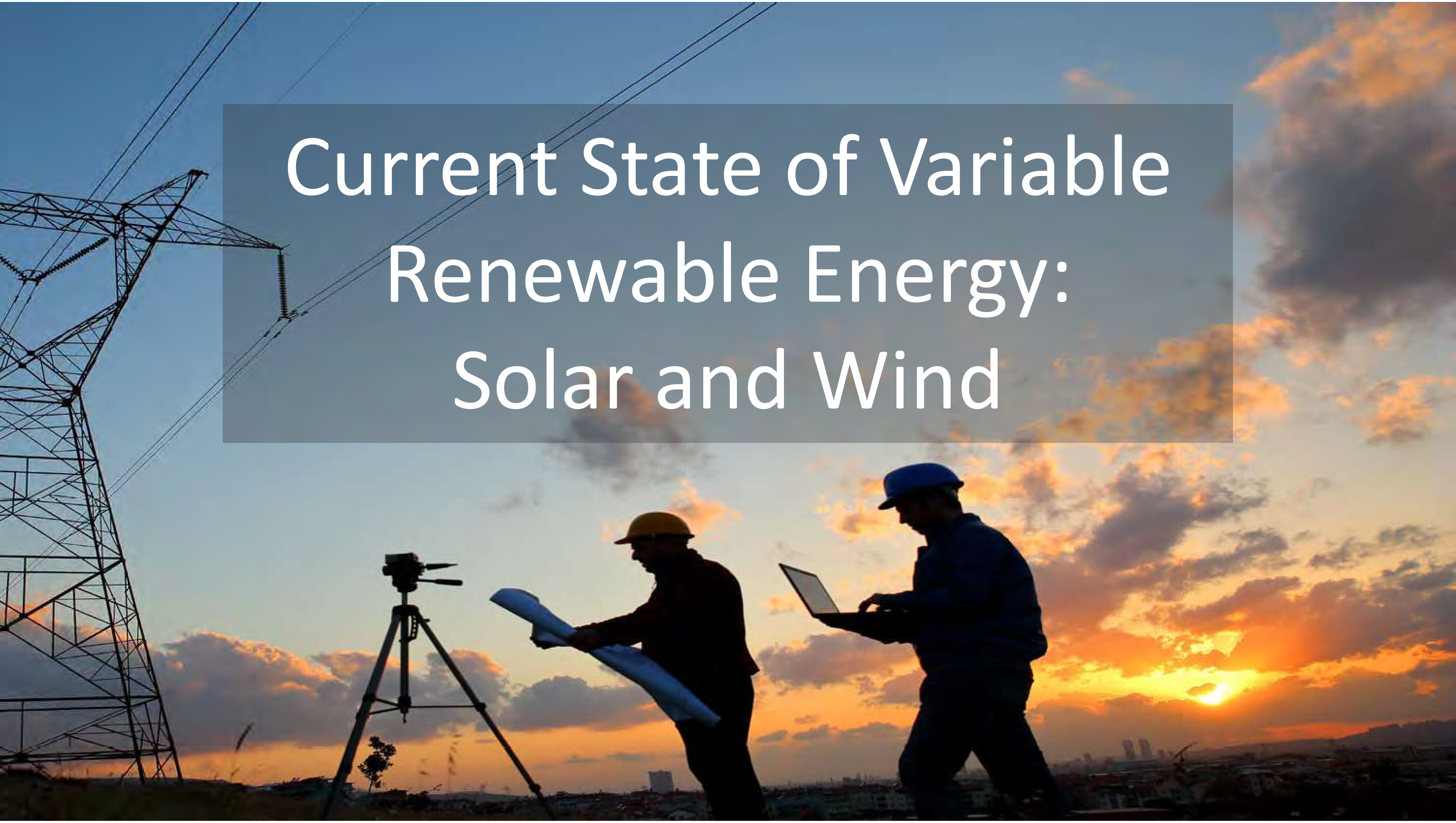


- More variable renewables
- More data
- More distributed resources

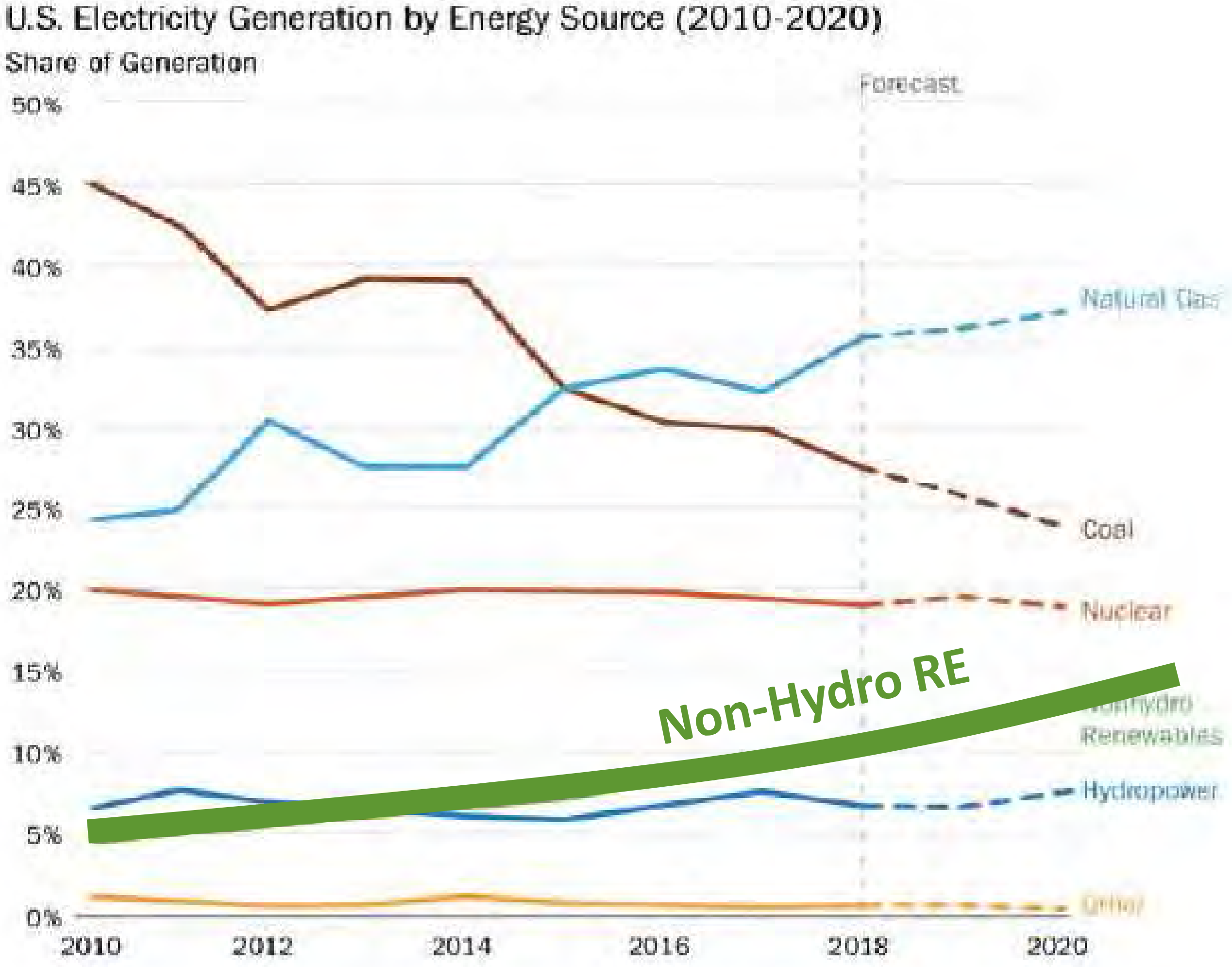
New challenges in a modern grid:

- Increasing levels of power electronics-based VRE: solar and wind
- More use of communications, controls, data, and information (e.g., smart grids)
- Other new technologies: electric vehicles (EVs), distributed storage, flexible loads
- Becoming highly distributed—more complex to control

Current State of Variable Renewable Energy: Solar and Wind



The US Energy supply is Shifting



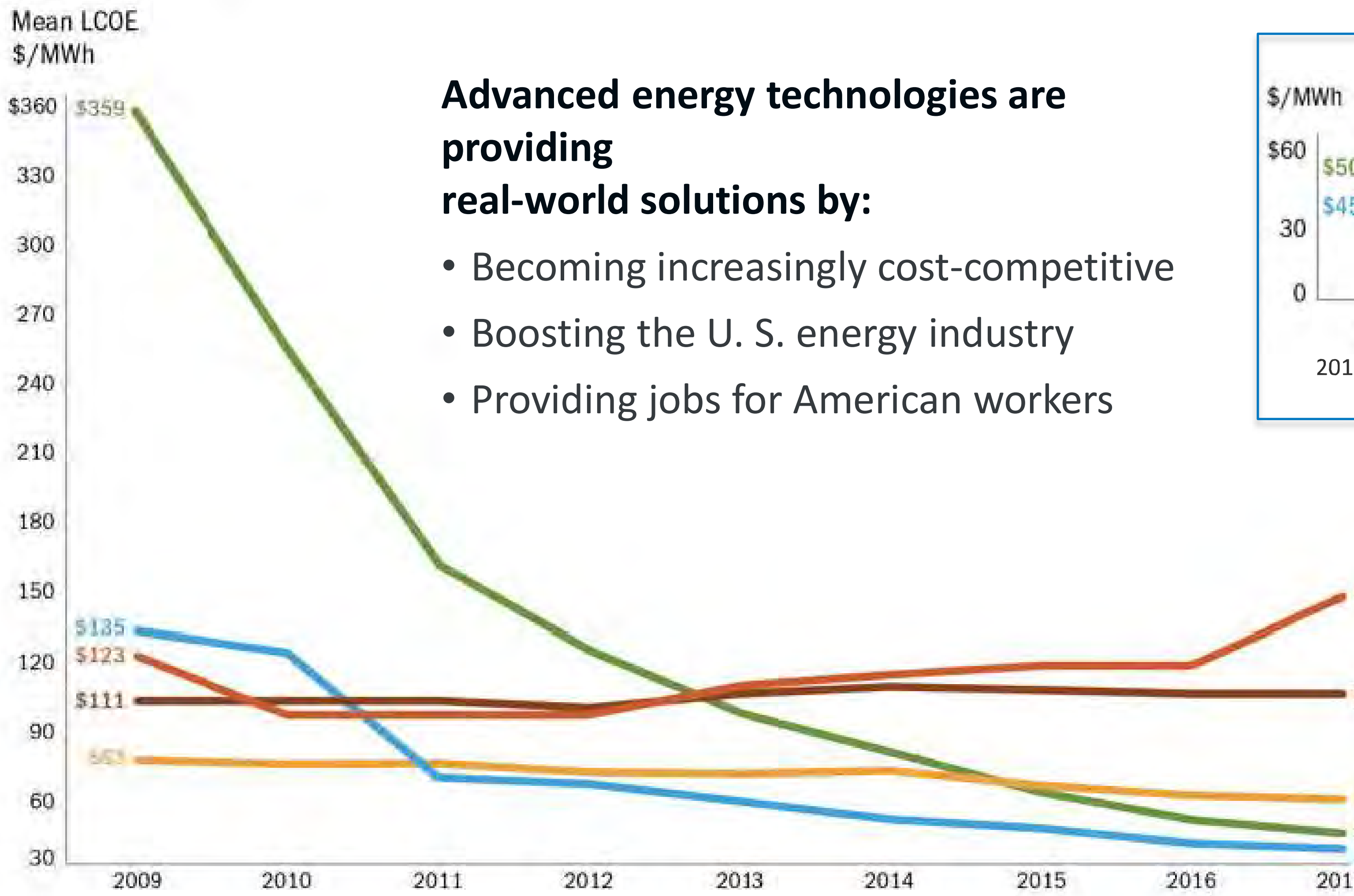
Source: United States Energy Information Agency, *Today in Energy,* 18 January 2019

Renewable Energy—not including hydropower—currently produces 10% of the total U.S. electricity generation. Within the next two years, this is expected to grow to 13%.

The Cost of Renewables is Falling

Advanced energy technologies are providing
real-world solutions by:

- Becoming increasingly cost-competitive
- Boosting the U. S. energy industry
- Providing jobs for American workers



Source: *Lazard's 2017 Levelized Cost of Energy Analysis,* Version 11, 2 November 2017

2019 Xcel pricing for projects due to go online in 2023.

Photovoltaic Systems – Large to Small

Solar Star

QUICK FACTS	
Location:	Rosamond, California
Capacity:	579 MW
Owner:	MidAmerican Solar, a subsidiary of MidAmerican Renewables
Design/Construction:	SunPower
Power Purchaser:	Southern California Edison
Technology:	SunPower™ Oasis™ Power Plant
No. of Modules:	Approx. 1,720,000
Equivalent No. of Homes Powered:	Approx. 255,000
Acres:	Approx. 3,200

Source: Sunpower, https://us.sunpower.com/sites/sunpower/files/media-library/fact-sheets/fs-solar-star-projects-factsheet.pdf

Anatolia Subdivision, Rancho Cordova, CA. Source: © 2015 Google, Map Data

Wind Plants

Alta Wind Energy Center, Tehachapi Pass, CA[1]
600 Vestas Wind Turbines
1,547 MW
2,680.6 GWh/yr

Shepard's Flats, Arlington, OR[3]
338 GE Turbines
845 MW
2,000 GWh/yr

Capricorn Ridge Wind Farm, Sterling and Coke County, TX[2]
407 GE and Siemens Turbines - 663 MW

Sources:
[1] https://en.wikipedia.org/wiki/Alta_Wind_Energy_Center
[2] http://www.nexteraenergyresources.com/pdf_redesign/capricornridge.pdf
[3] https://en.wikipedia.org/wiki/Shepherds_Flat_Wind_Farm

New Capacity Additions are Gas, Wind and Solar

Source: https://www.energy.gov/sites/prod/files/2019/08/f65/2018%20Wind%20Technologies%20Market%20Report%20FINAL.pdf

South Africa

Table 5: IRP 2019

	Coal	Coal (Decommissioning)	Nuclear	Hydro	Storage	PV	Wind	CSP	Gas & Diesel	Other (Distributed Generation, CoGen, Biomass, Landfill)
Current Base	37 149		1 860	2 100	2 912	1 474	1 980	300	3 830	499
2019	2 155	2373					244	300		Allocation to the extent of the short term capacity and energy gap.
2020	1 433	557				114	300			
2021	1 433	1403				300	818			
2022	711	844			513	400 / 1000	1600			
2023	750	555				1000	1600			500
2024			1860				1600		1000	500
2025						1000	1600			500
2026		1219					1600			500
2027	750	847					1 600		2000	500
2028		475				1000	1 600			500
2029		1694			1575	1000	1 600			500
2030		1050		2 500		1 000	1 600			500
TOTAL INSTALLED CAPACITY by 2030 (MW)	33364		1860	4600	5000	8288	17742	600	6380	
% Total Installed Capacity (% of MW)	43		2.36	5.84	6.35	10.52	22.53	0.76	8.1	
% Annual Energy Contribution (% of MWh)	58.8		4.5	8.4	1.2*	6.3	17.8	0.6	1.3	

- Installed Capacity
- Committed / Already Contracted Capacity
- Capacity Decommissioned
- New Additional Capacity
- Extension of Koeberg Plant Design Life
- Includes Distributed Generation Capacity for own use

2030 IRP

6.3% PV

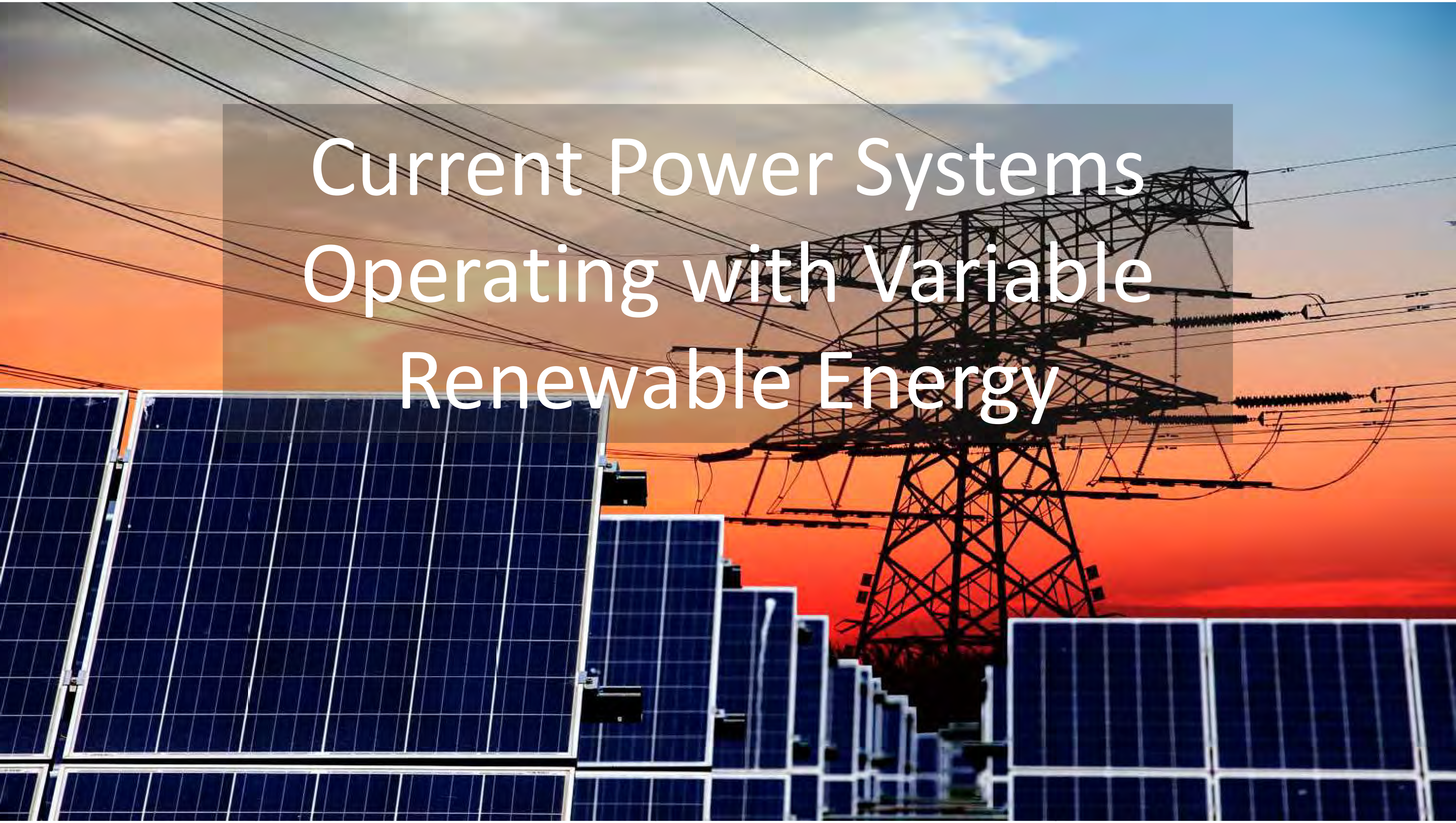
0.6% CSP

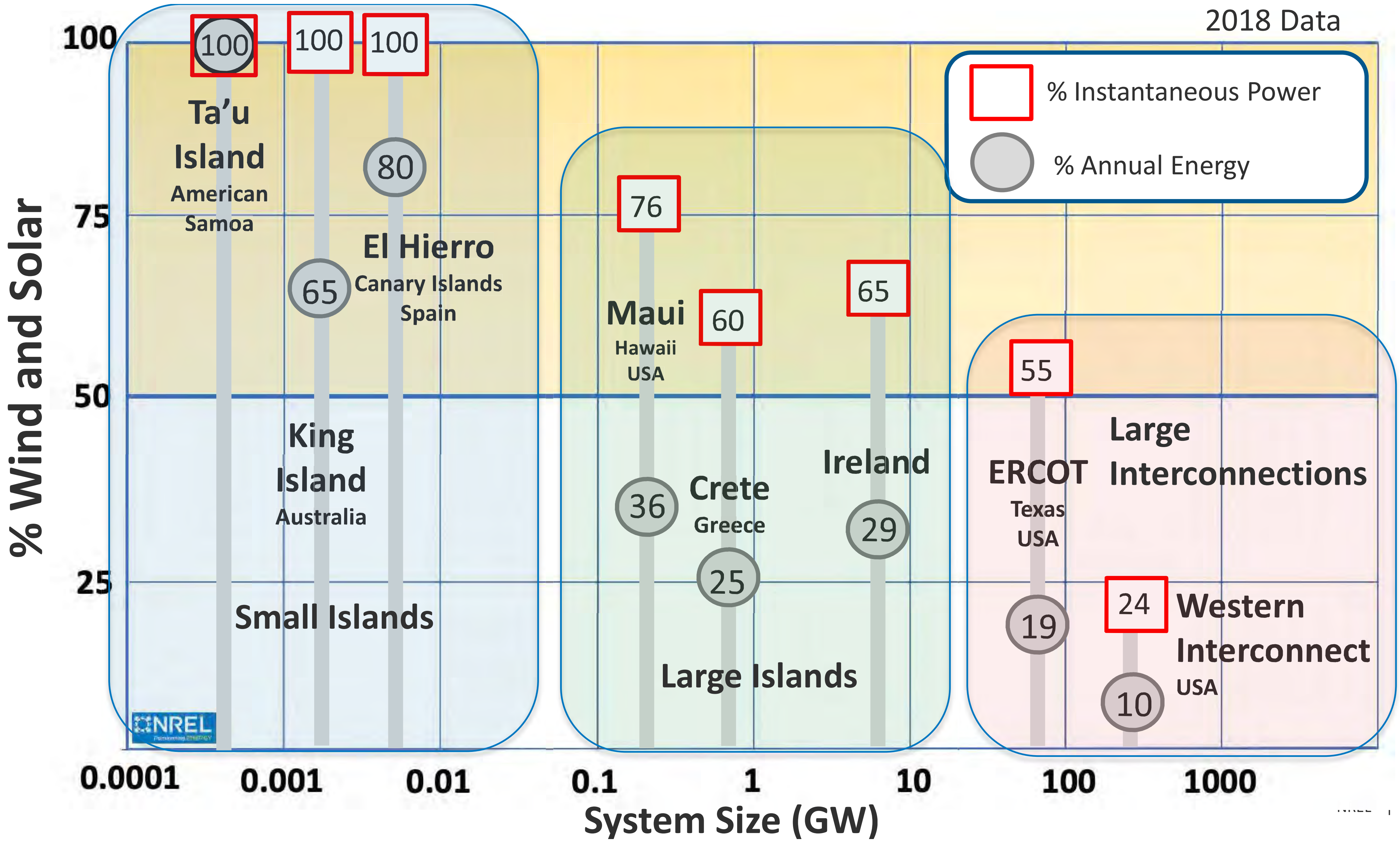
17.8% Wind

~25% wind/solar

Source: Eskom IRP

https://www.egsa.org.za/wp-content/uploads/2019/10/IRP-2019_corrected-as-gazetted-18-October-2019-No.-42784.pdf


Current Power Systems
Operating with Variable
Renewable Energy


2018 Data
% Instantaneous Power
% Annual Energy
% Wind and Solar
100
75
50
25
0.0001
0.001
0.01
0.1
1
10
100
1000
System Size (GW)
Small Islands
Ta'u Island
American Samoa
100
100
King Island
Australia
100
65
El Hierro
Canary Islands Spain
100
80
Large Islands
Maui
Hawaii USA
76
36
Crete
Greece
60
25
Ireland
65
29
Large Interconnections
ERCOT
Texas USA
55
19
Western Interconnect
USA
24
10
NREL

Western Wind and Solar integration Study

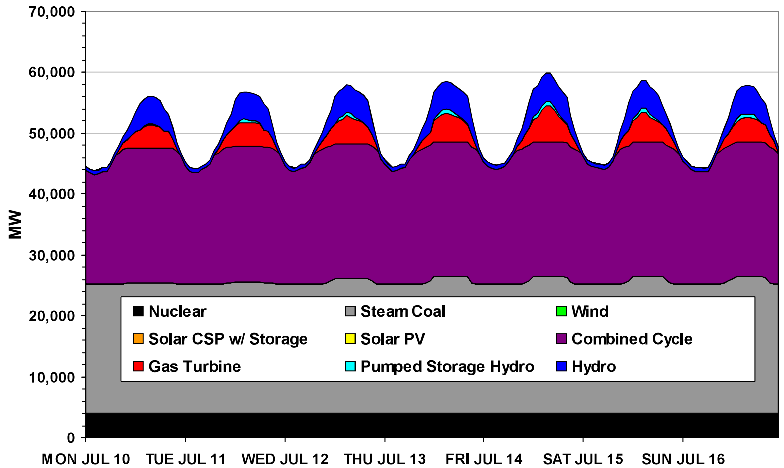
- **Goal:**
  - To understand the costs and operating impacts due to the variability and uncertainty of wind, PV and concentrating solar power on the WestConnect grid.
- **Utilities:**
  - Arizona Public Service
  - El Paso Electric
  - NV Energy
  - Public Service Company of New Mexico
  - Salt River Project
  - Tri-State Generation & Transmission
  - Tucson Electric Power
  - Xcel Energy
  - Western Area Power Administration.

Can we integrate 35% renewables in the West?

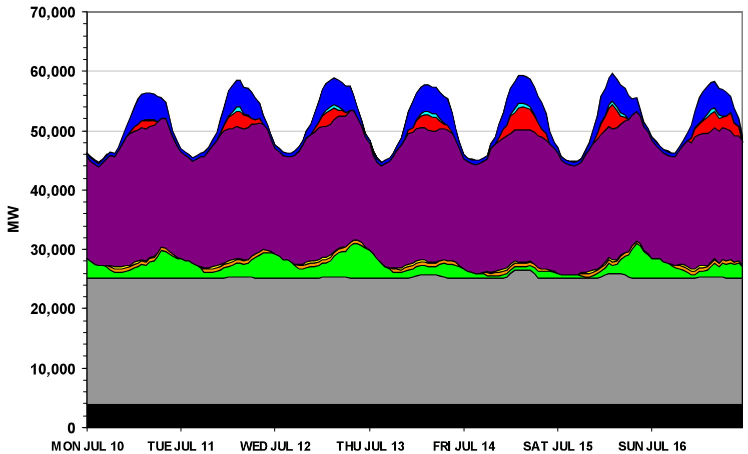
Source: NREL, Western Wind and Solar Integration Study (WWSIS) (2007–2015), http://www.nrel.gov/grid/wwsis.html

Dispatch During a “Tame” Week - July

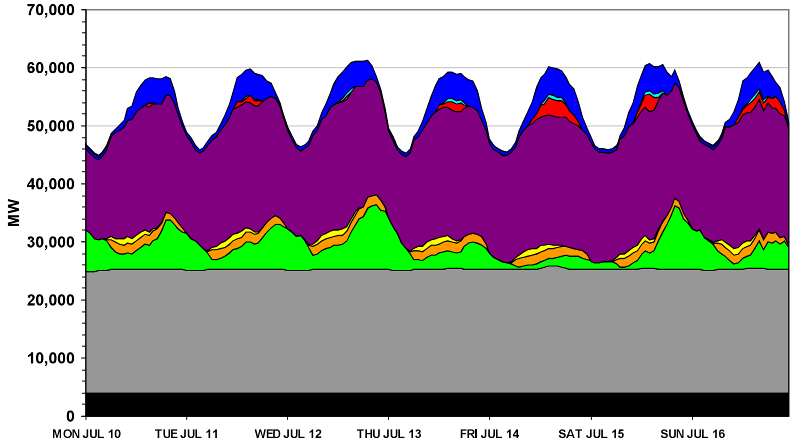
No wind



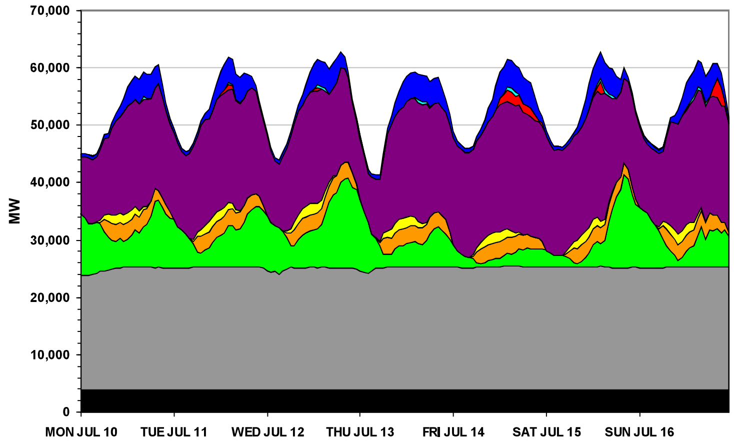
10% wind



20% wind

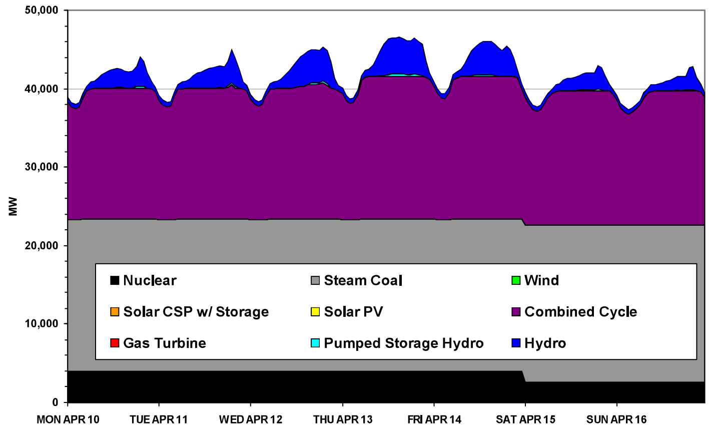


30% wind

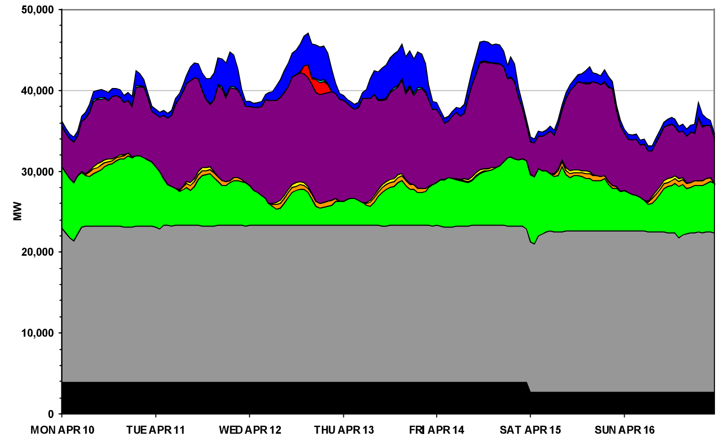


Not so "Tame" Week - April

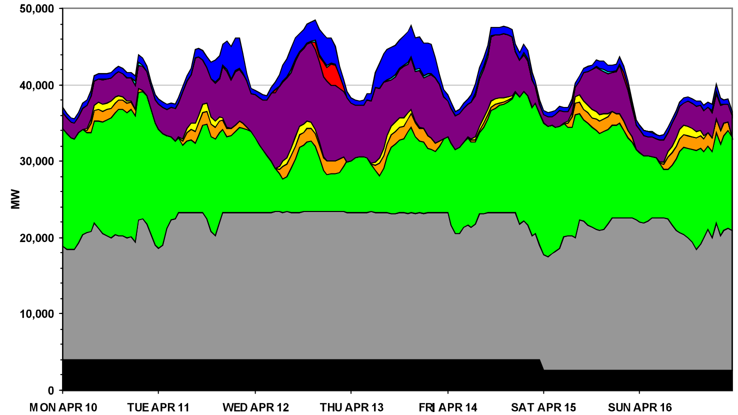
No wind



10% wind

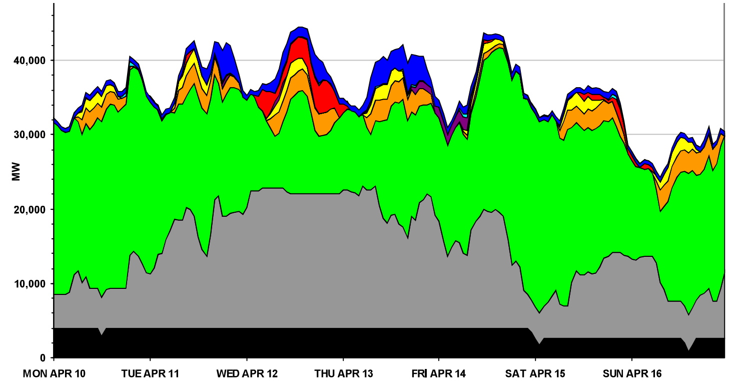


20% wind



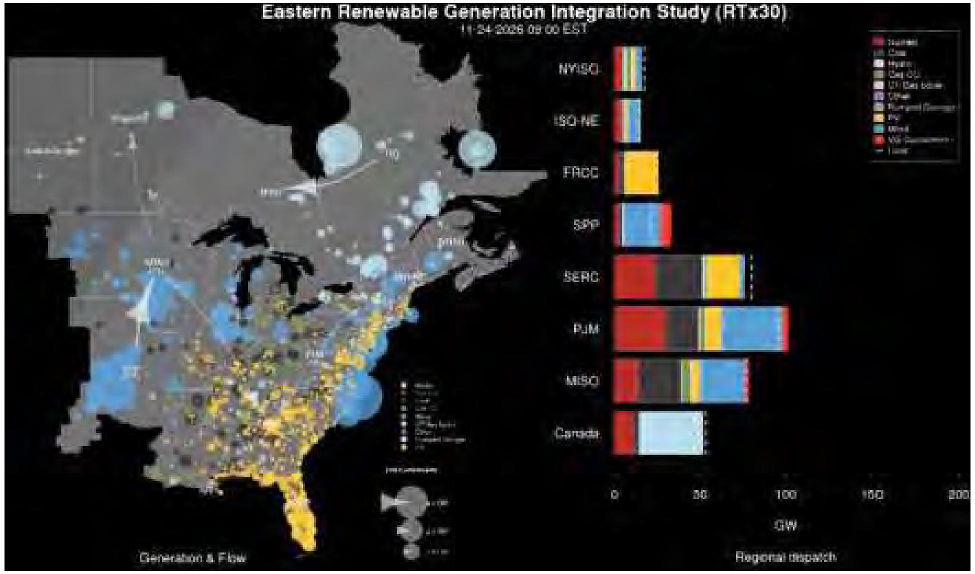
30% wind

(Coal is cycling, and nuclear is being impacted; it is likely that wind will need to be curtailed. But the grid can be operated in a reliable manner.)



Eastern Renewable Generation Integration Study

- **Goals:**
  - Operational impact of 30% wind and solar penetration on the Eastern Interconnection at a 5-minute resolution
  - Efficacy of mitigation options in managing variability and uncertainty in the system.

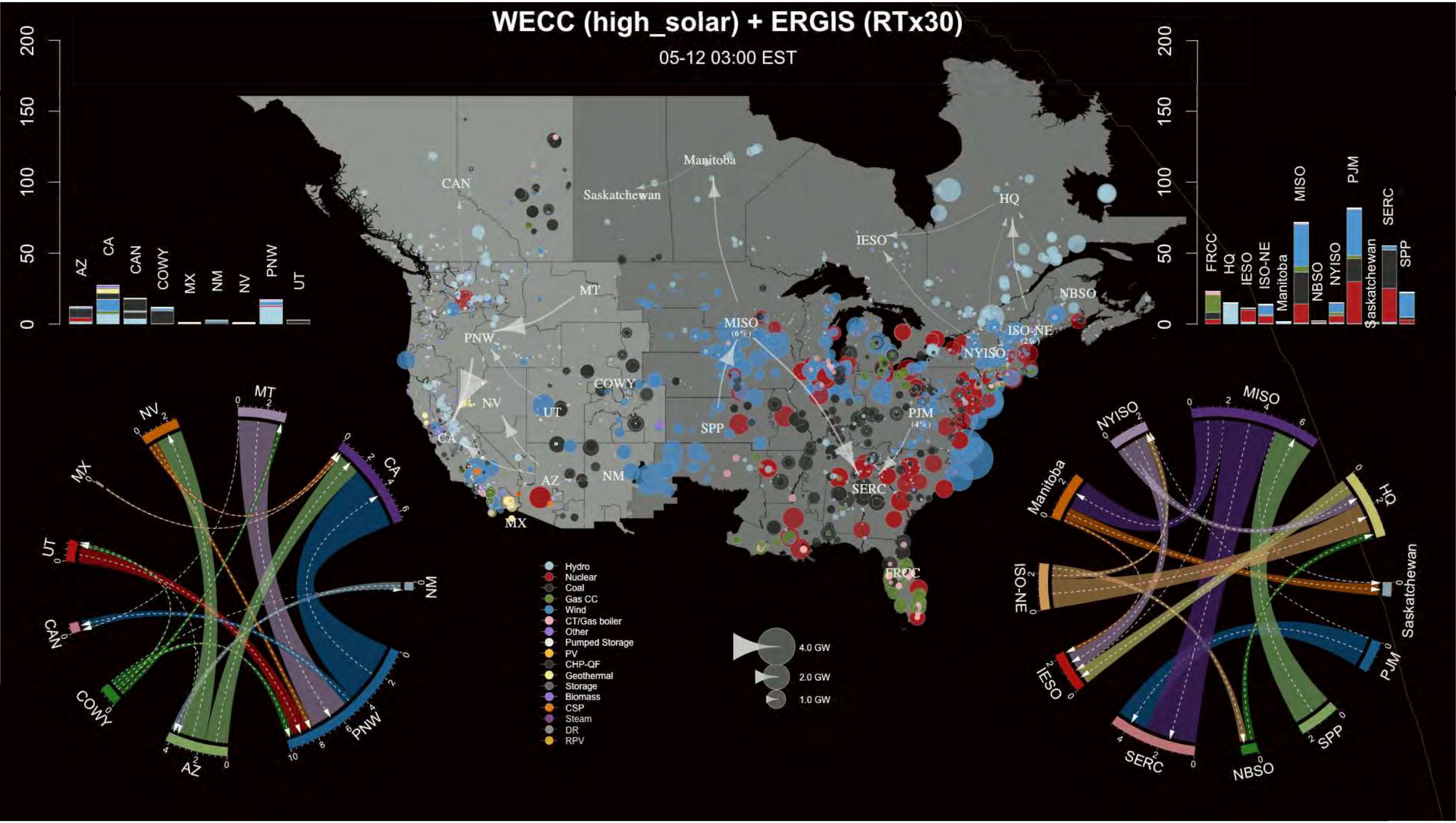


Operational areas of interest:

- Reserves
  - Types
  - Quantities
  - Sharing.
- Commitment and dispatch:
  - Day-ahead
  - Four-hour-ahead
  - Real-time.
- Inter-regional transactions:
  - 1-hour
  - 15-minute
  - 5-minute.

Impact
Demonstrated that very large power systems can operate at a 5-min dispatch with 30% VRE.

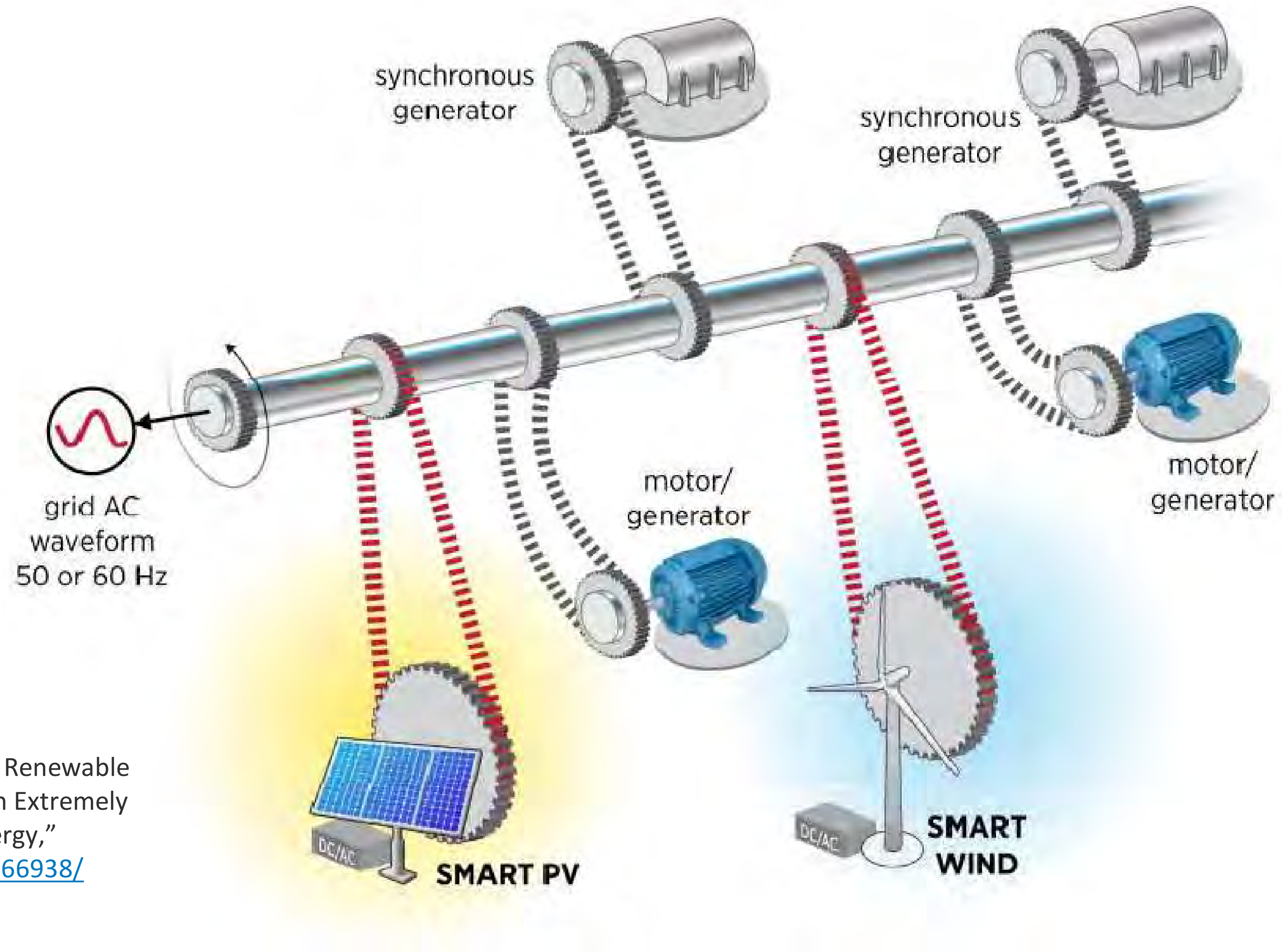
Source: NREL, Eastern Renewable Generationntegration Study (ERGIS) (2016), http://www.nrel.gov/grid/ergis.html



WECC (high_solar) + ERGIS (RTx30)
05-12 03:00 EST
AZ
CA
CAN
COWY
MX
NM
NV
PNW
UT
FRCC
HQ
IESO
ISO-NE
Manitoba
MISO
NBSO
NYISO
PJM
Saskatchewan
SERC
SPP
Saskatchewan
MISO (6%)
PJM (4%)
ISO-NE (2%)
MT
Hydro
Nuclear
Coal
Gas CC
Wind
CT/Gas boiler
Other
Pumped Storage
PV
CHP-QF
Geothermal
Storage
Biomass
CSP
Steam
DR
RPV
4.0 GW
2.0 GW
1.0 GW

Changing from Synchronous Generators to Power Electronics

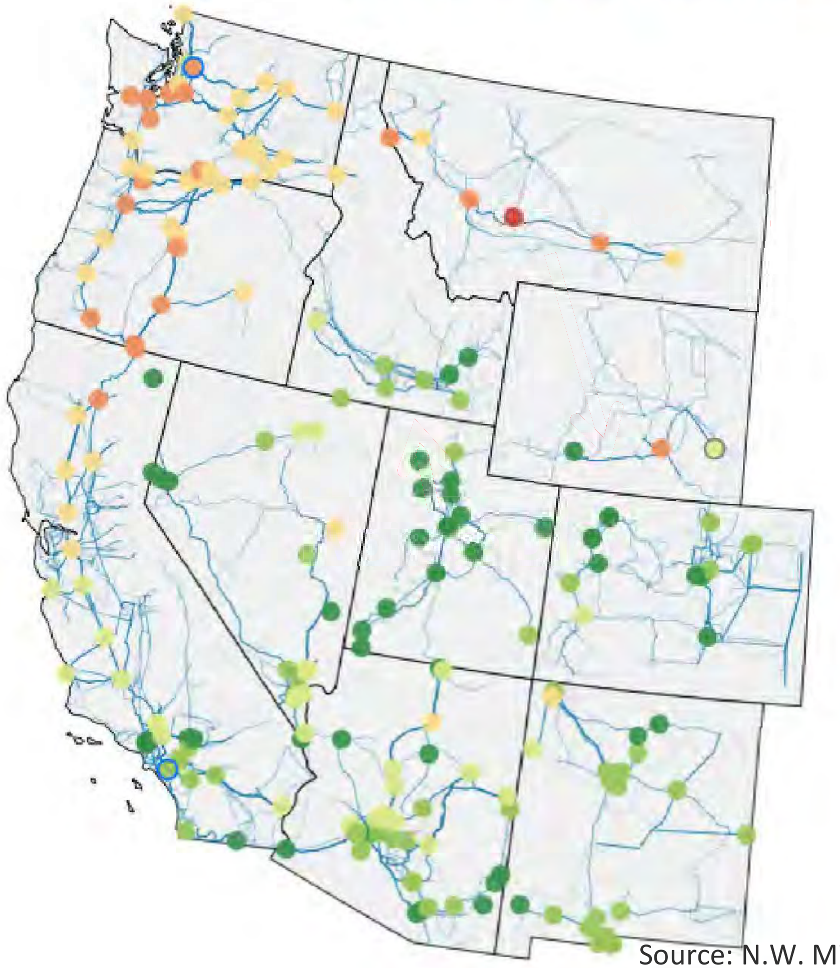
Need advanced controls and technologies to integrate wind and solar while maintaining grid stability and reliability



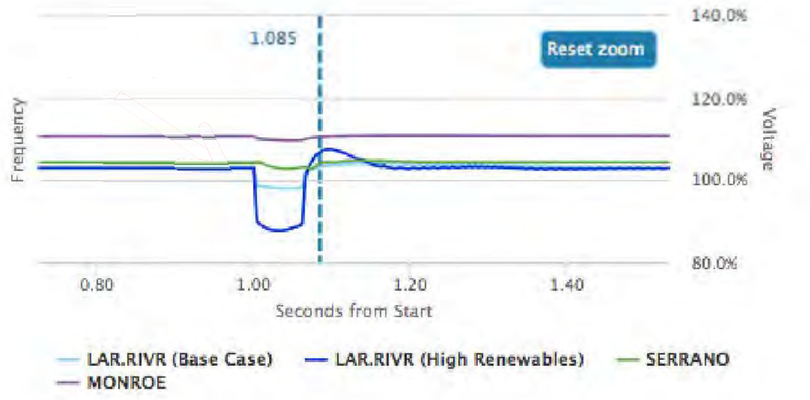
Source: B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/

System Stability

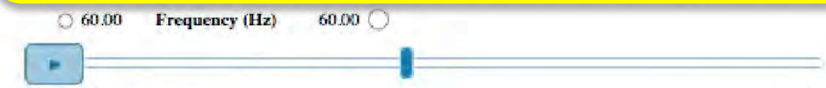
Western Wind and Solar Integration Study



- **Wind power plants:** voltage regulation and ride-through
- **Utility-scale PV:** voltage regulation and ride-through
- **Rooftop PV:** embedded in composite load model, no controls.



Impact:
Western Interconnection can survive a major contingency outage with 30% variable generation (inverter-based).

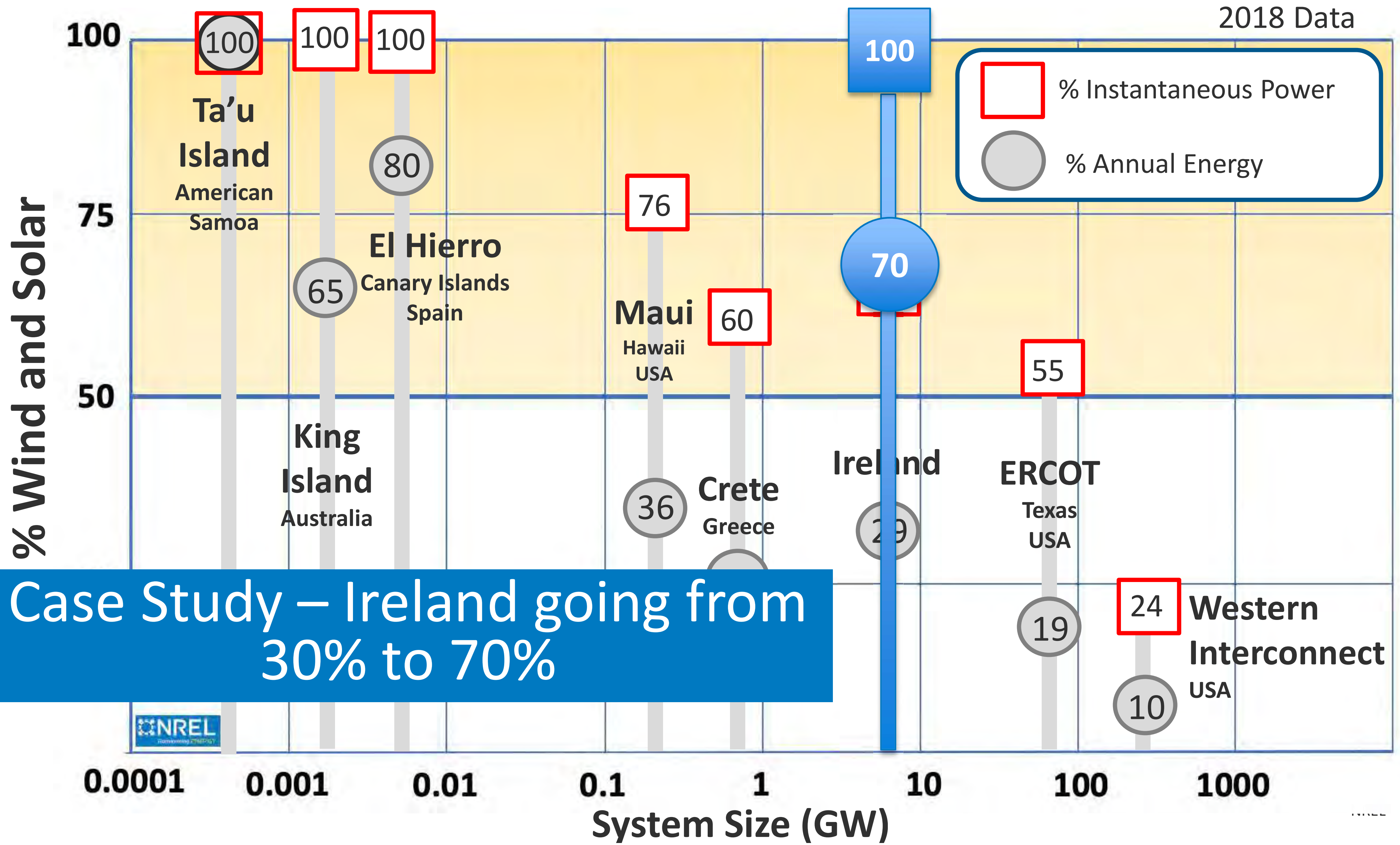


Source: N.W. Miller et al., *WWSIS: Phase 3A*, http://www.nrel.gov/docs/fy16osti/64822.pdf

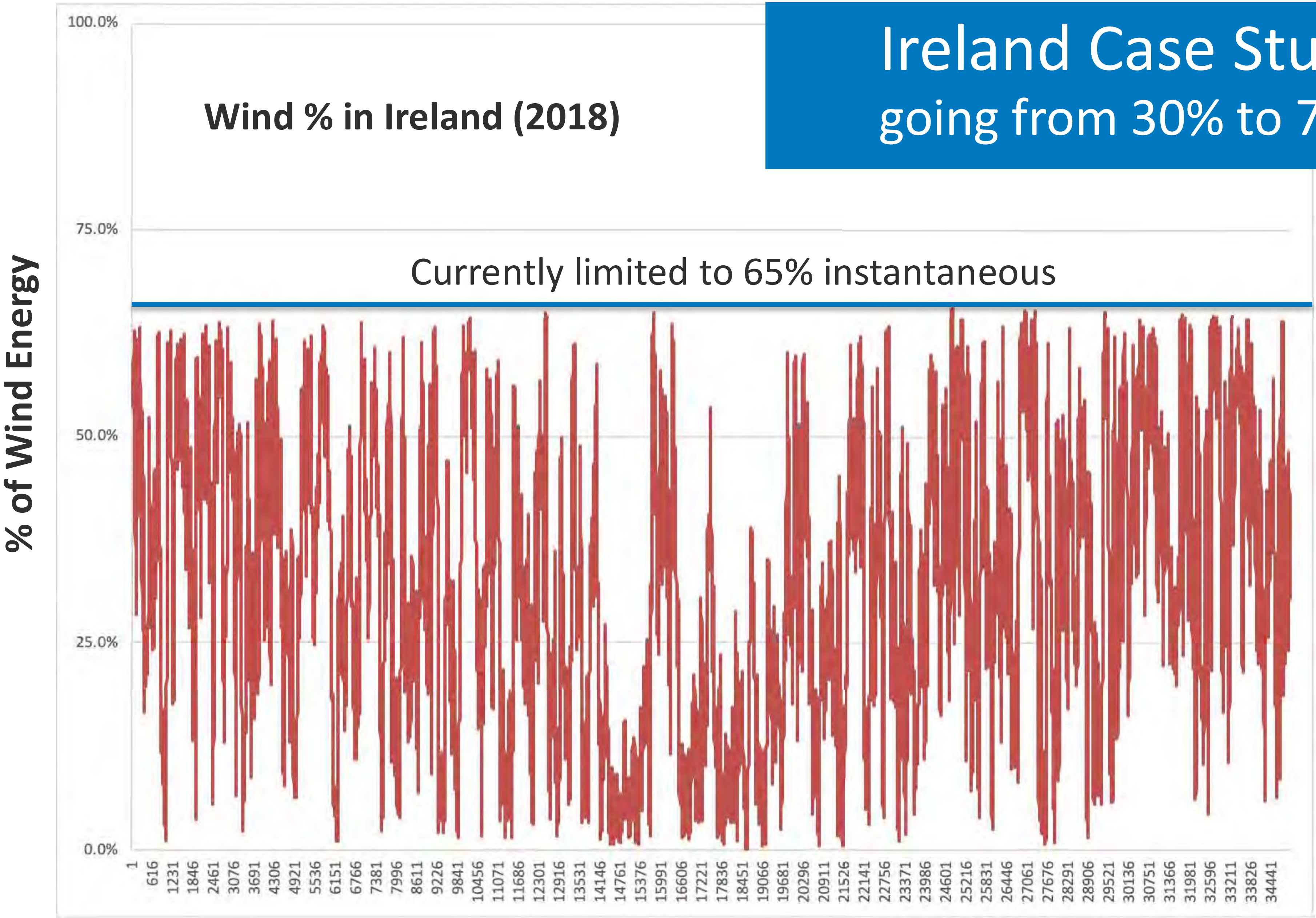
We have done the research and demonstrated that achieving 30% VRE is possible with minimal system changes.

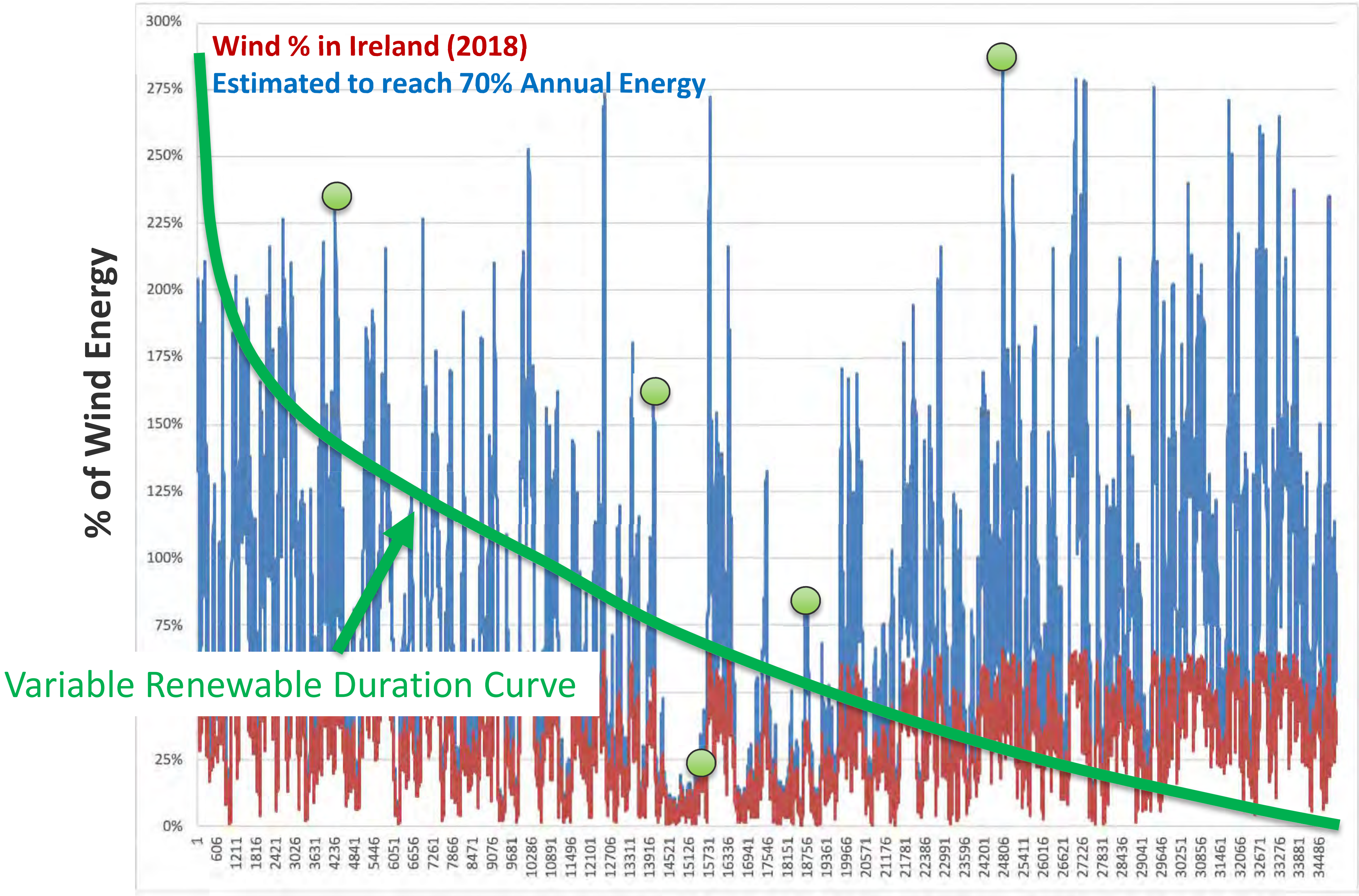
What do we need to do to achieve very high levels (more than 50%) of wind and solar integration?

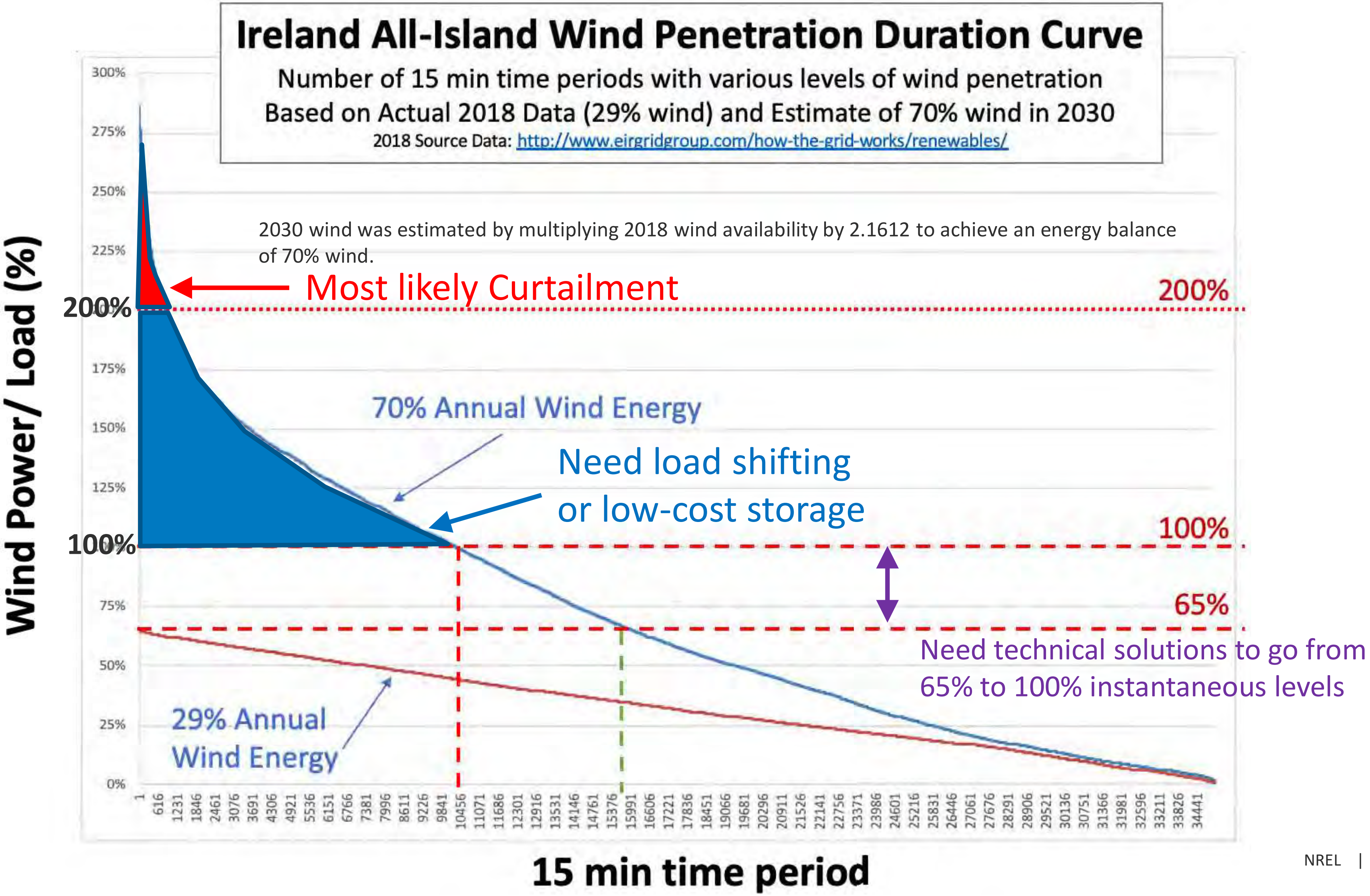
Case Study – Ireland going from 30% to 70%



Ireland Case Study
going from 30% to 70%

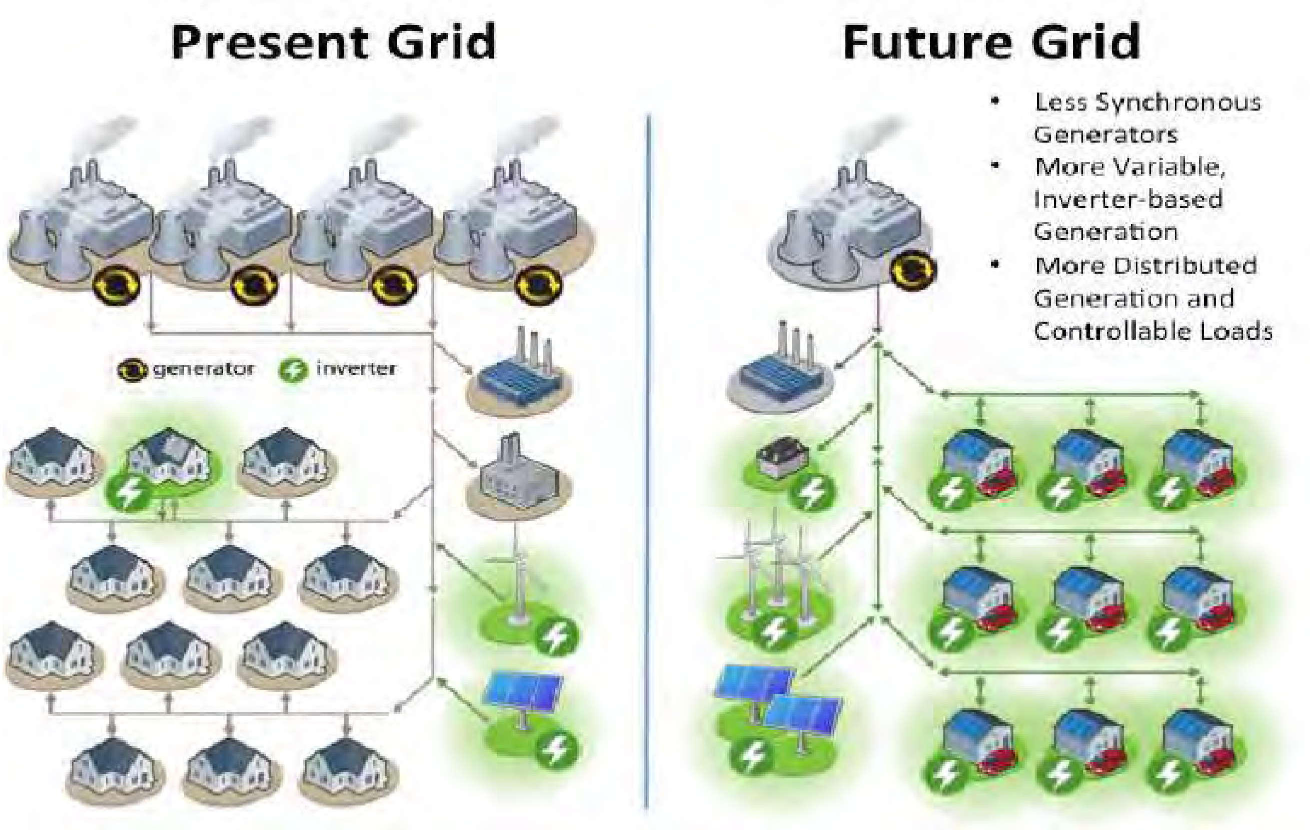



Wind % in Ireland (2018)
Estimated to reach 70% Annual Energy
% of Wind Energy
Variable Renewable Duration Curve
300%
275%
250%
225%
200%
175%
150%
125%
100%
75%
25%
0%



Ireland All-Island Wind Penetration Duration Curve
Number of 15 min time periods with various levels of wind penetration
Based on Actual 2018 Data (29% wind) and Estimate of 70% wind in 2030
2018 Source Data: http://www.eirgridgroup.com/how-the-grid-works/renewables/
2030 wind was estimated by multiplying 2018 wind availability by 2.1612 to achieve an energy balance of 70% wind.
Most likely Curtailment
200%
70% Annual Wind Energy
Need load shifting
or low-cost storage
100%
65%
Need technical solutions to go from
65% to 100% instantaneous levels
29% Annual
Wind Energy
Wind Power/ Load (%)
15 min time period

Technical Challenges with Ultra-high Levels of VRE



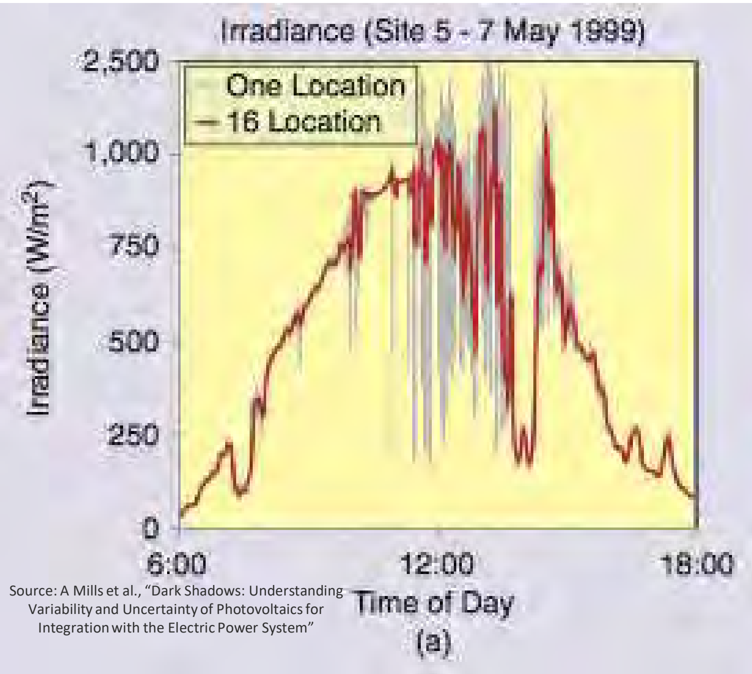
- Variability and uncertainty of VRE
- Power system stability
- Protection coordination
- Unintentional islanding
- Black-start capability

Source: B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/

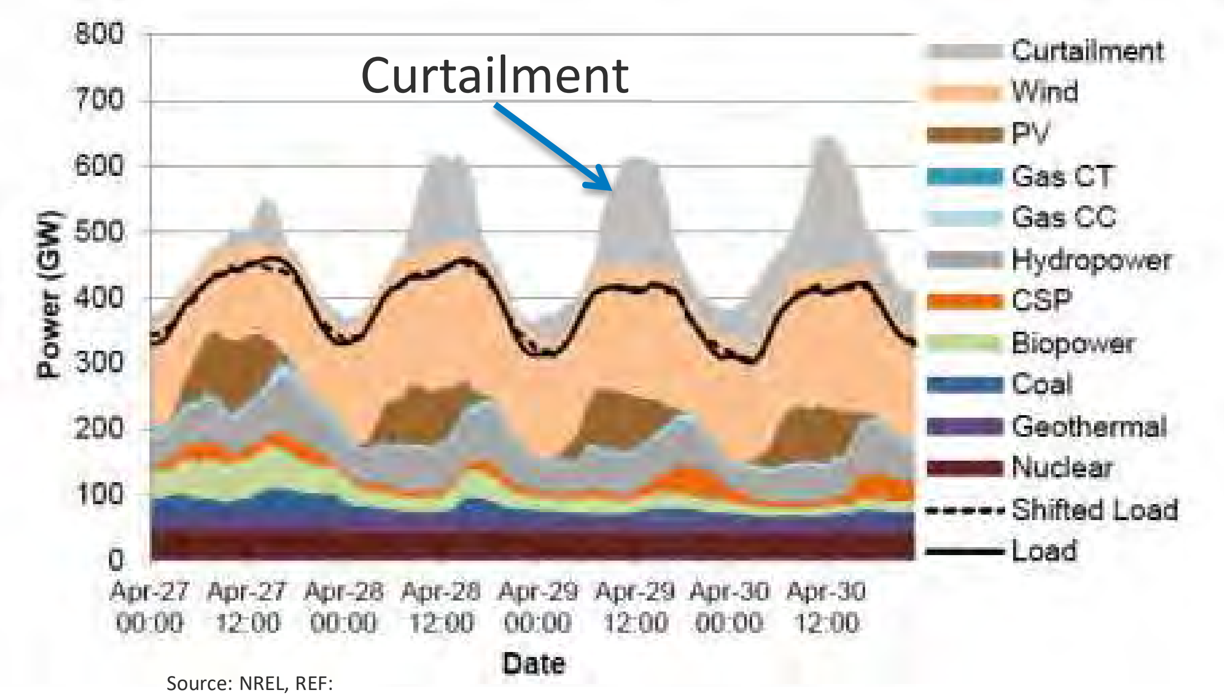
Variability and Uncertainty

Challenges:

- **Energy shifting** (VRE produces energy when resources are available—variable and uncertain)
- **Forecasting** (renewable resources and load)

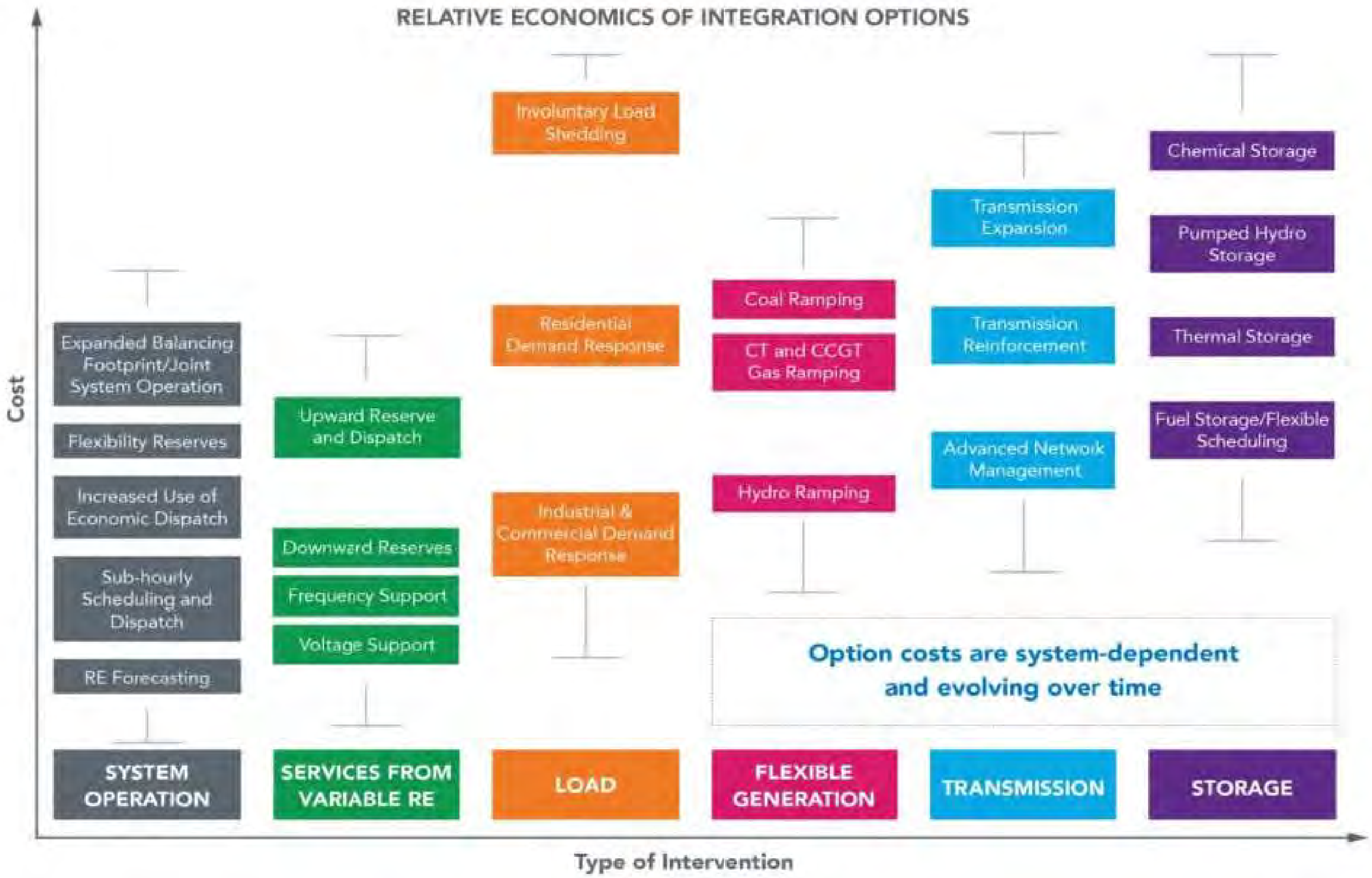


Source: A Mills et al., "Dark Shadows: Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System"



Source: NREL, REF: 80% Renewables Case, http://www.nrel.gov/analysis/re_futures/

Options for Dealing with Variability and Uncertainty

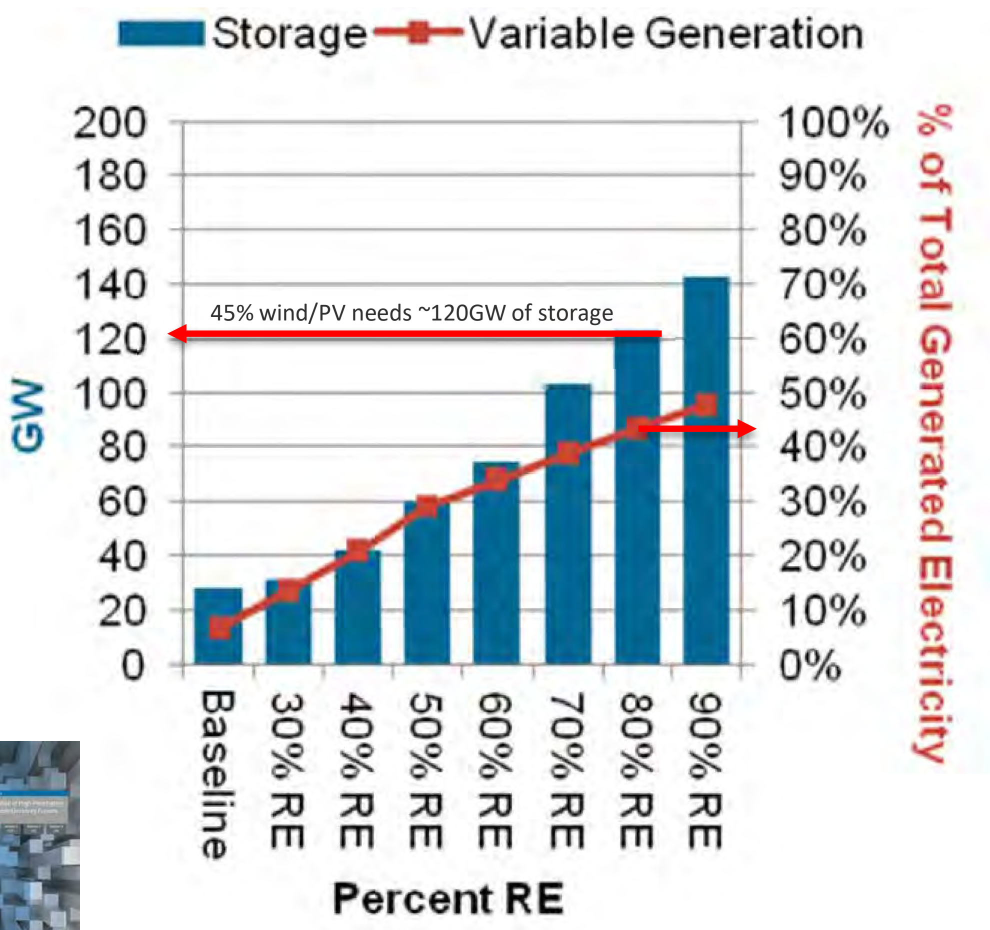


Source: J. Cochran et al., *Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy*, http://www.nrel.gov/docs/fy15osti/62607.pdf

Solutions:

- Utilize geographic diversity.
- Utilize flexible conventional generation.
- Increase sharing among balancing authority areas.
- Expand the transmission system.
- Curtail excess VRE production.
- Coordinate flexible loads (active demand response).
- Enhance VRE and load forecasting.
- Add electrical storage.
- Interact with other energy carriers.

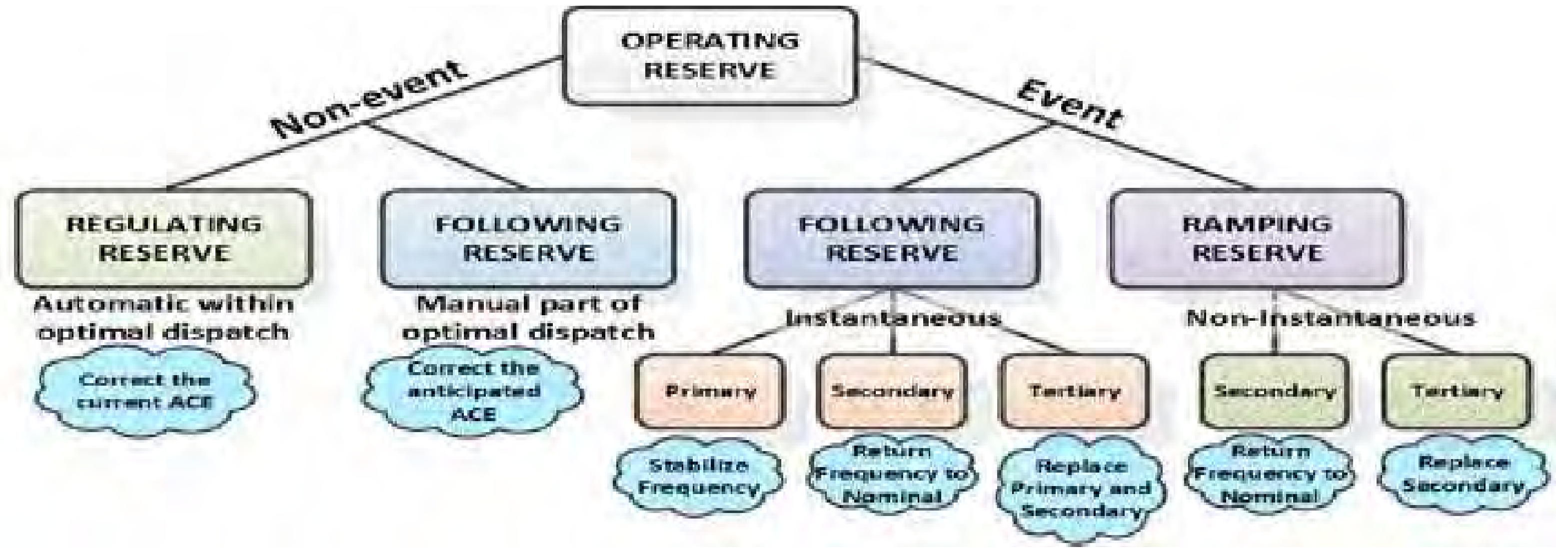
Energy Storage – How Much do we Need?



- NREL's Renewable Electricity Futures Study (2012) estimated the amount of energy storage needed for various penetrations of renewable energy (RE) for the continental US in 2050.
- RE included all types of renewables including hydro
- The figure on the left shows GW of storage capacity (Y1-axis), % variable generation (Y2-axis) and % total RE energy (x-axis)
- **For the 80% RE scenario (that has 45% wind and PV) the estimated storage need was ~120GW of 8hr storage.**
- For context, currently there is 22GW of pumped hydro and 1 GW of batteries installed in the US.
- The difference between current levels and 120GW could be made from a variety of new storage technologies, shiftable loads, hydrogen, etc.

Source: Renewable Electricity Futures Study (Entire Report)
National Renewable Energy Laboratory. (2012). Renewable Electricity Futures Study. Hand, M.M.; Baldwin, S.; DeMeo, E.; Reilly, J.M.; Mai, T.; Arent, D.; Porro, G.; Meshek, M.; Sandor, D. eds. 4 vols. NREL/TP-6A20-52409. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/analysis/re-futures.html

Power System Stability



Challenges:

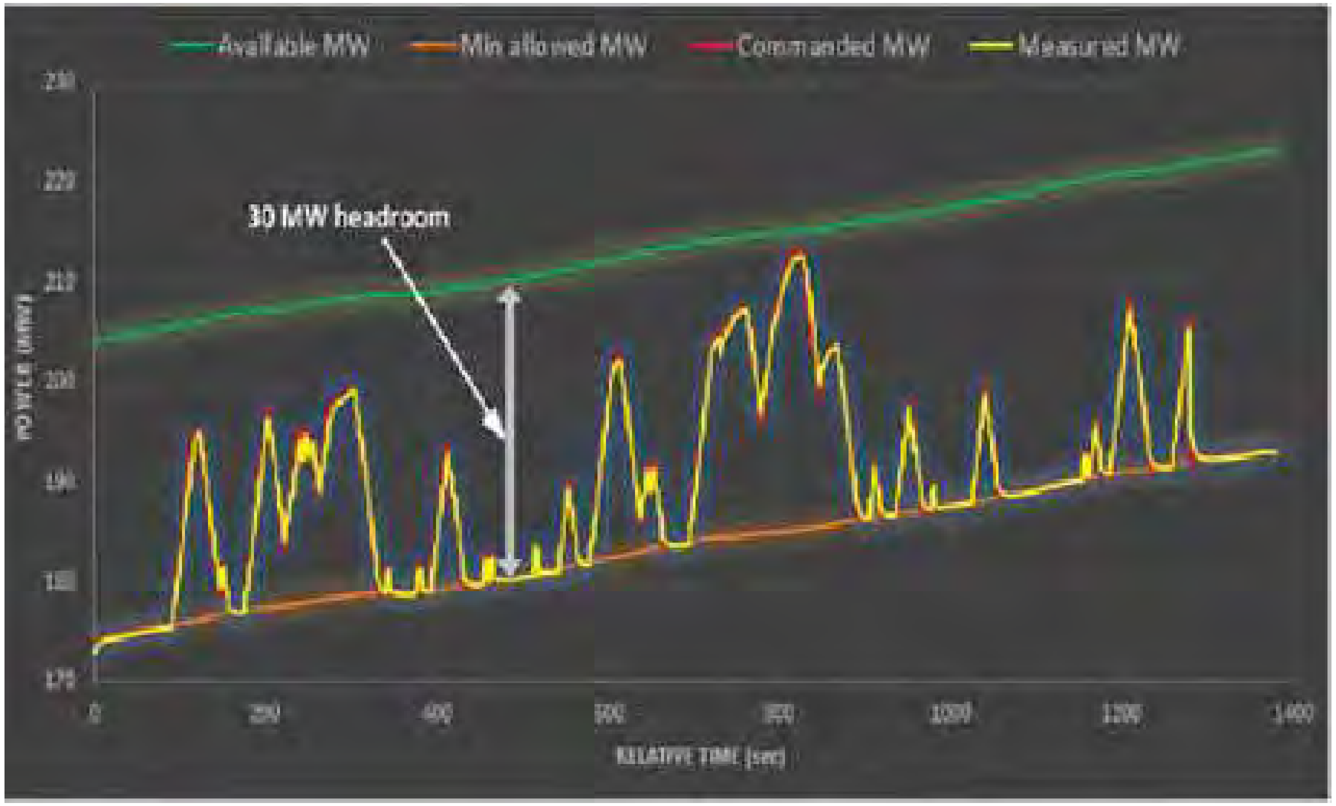
- **Transient and dynamic stability** (loss of system inertia could reduce ability to respond to disturbances—need ride-though capabilities in VRE)
- **Frequency regulation** (need primary, secondary, and tertiary response from VRE)
- **Volt/VAR regulation** (need ability to locally change voltage to stay within nominal limits)

Solutions:

- Use smart inverters with advanced functionality.
- Mimic synchronous generator characteristics.
- Provide active power, reactive power, voltage, and frequency control.

Inverter Based Resources can Provide Grid Services

NREL/FirstSolar/CAISO experiment: 300-MW plant following AGC signal



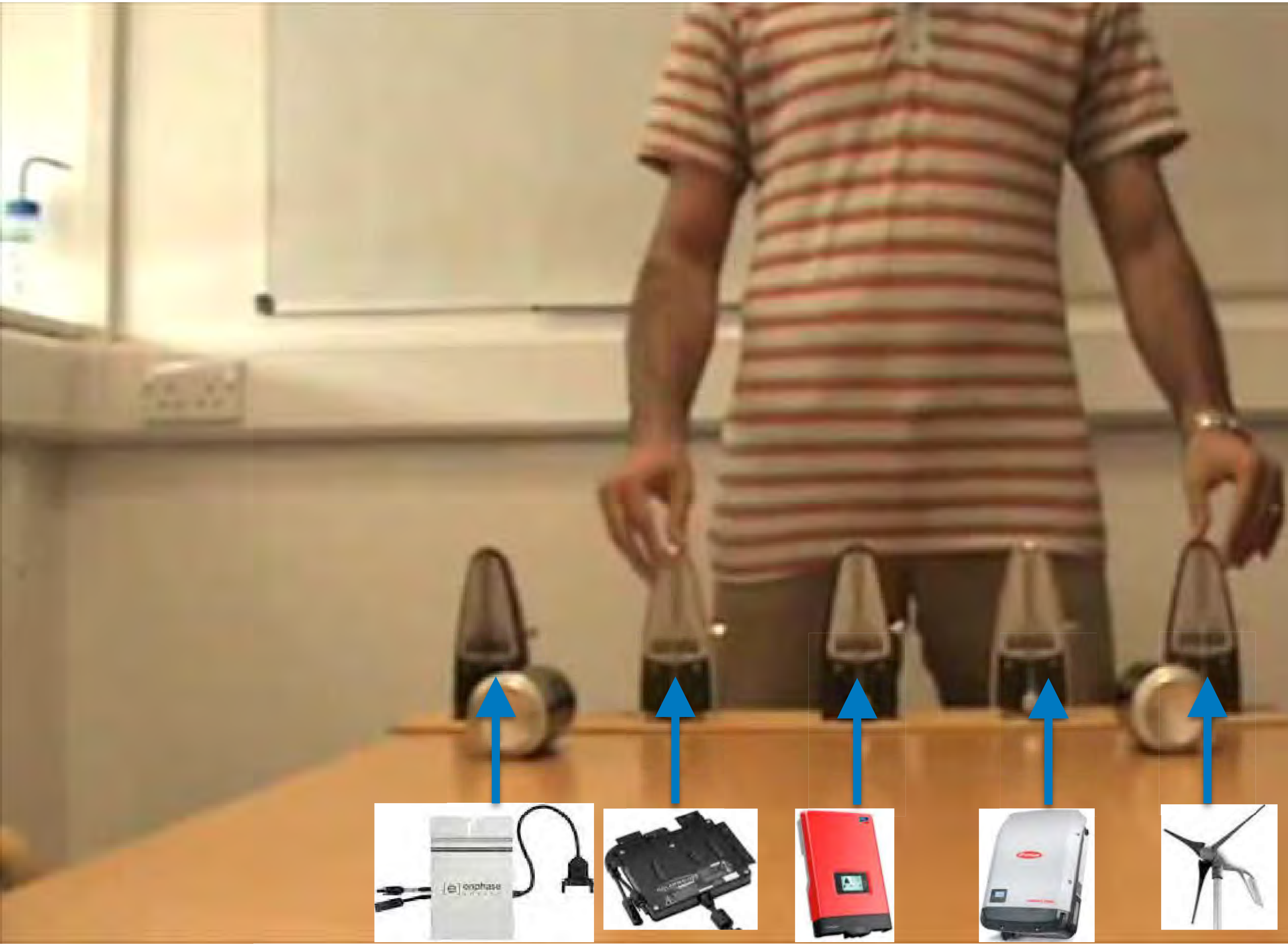
We demonstrated that PV plants (and wind power plants) can deliver essential grid services.

300-MW PV Plant in California

Photo from First Solar

Source: C. Loutan et al., *Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant*, http://www.nrel.gov/docs/fy17osti/67799.pdf

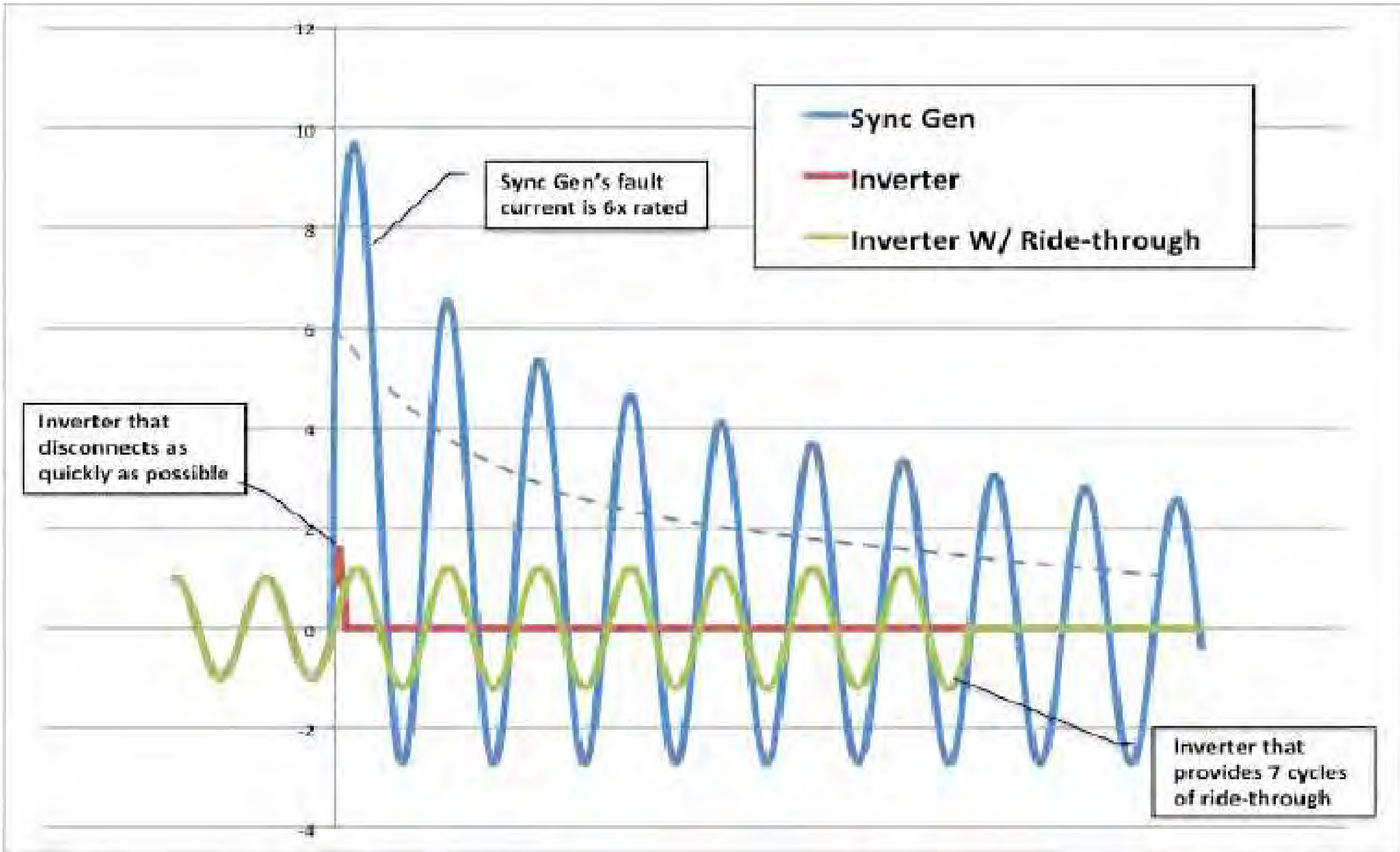
SunShot U.S. Department of Energy



Using these physics principles, **Virtual Oscillator Control (VOC)** allows for self-synchronizing inverters

B. B. Johnson, S. V. Dhople, A. O. Hamadeh, and P. T. Krein, "Synchronization of Parallel Single-Phase Inverters With Virtual Oscillator Control," *IEEE Trans. Power Electron.*, vol. 29, pp. 6124–6138, November 2014.

Additional Technical Challenges



Source: B. Kroposki et al., "Achieving a 100% Renewable Grid – Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy," http://ieeexplore.ieee.org/document/7866938/

Challenges:

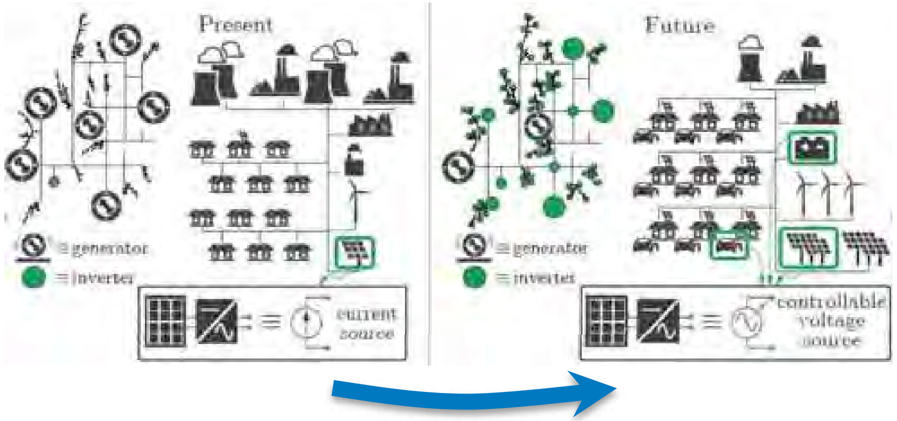
- **Protection coordination** (loss of high short-circuit current may effect protection schemes)
- **Unintentional islanding** (need methods to protect against unintentional islanding)
- **Black-start**—ability to restore system from outage
- **Distributed controls.**

Solutions:

- **Protection coordination**—synchronous condensers, new protection schemes
- **Unintentional islanding**—New artificial intelligence options
- **Black-start**—New system restoration methods
- **Distributed controls**—new control architectures and management systems.

How to control millions of devices?

As we migrate from a centrally controlled, synchronous generator-based grid to a highly distributed, inverter-based system…



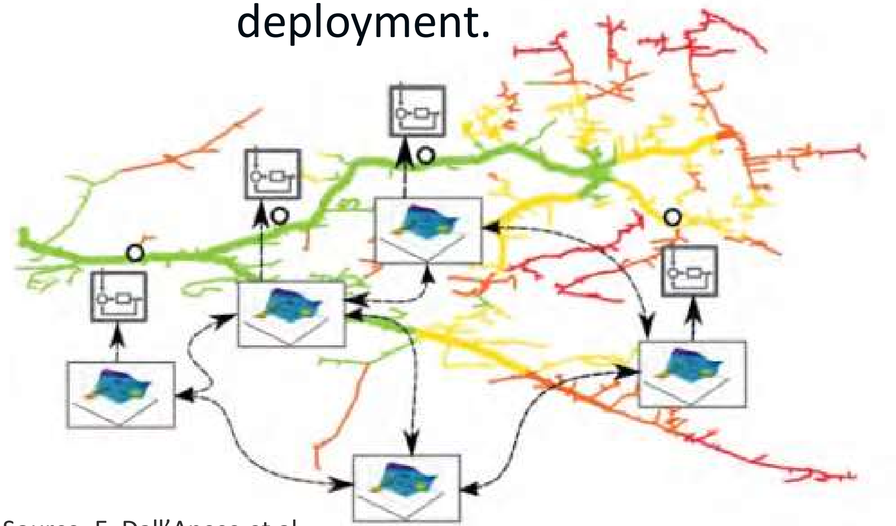
We need smart inverters with advanced functionality to maintain grid stability and…

Improved optimization for millions of controllable devices in the grid.

Source: ARPA-E, http://www.arpa-e.energy.gov/?q=arpa-e-programs/nodes

Research Needs

- Control theory
- Advanced control and optimization algorithms
- Imbedded controllers in devices
- Linkage to advanced distribution management systems (ADMS)
- Validation of concepts and deployment.



Source: E. Dall'Anese et al., http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6920041

Advancing Technologies through Grid Simulation and Experimentation

NREL Grid Simulation and Experimentation Capabilities

Grid Simulation and Data Capabilities

- High Performance Computing (Eagle)
- Large-scale Renewable Integration Studies
- Integrated Transmission, Distribution, Communications, and Markets Grid Co-simulation platform (HELICS)
- Synthetic Grid Datasets
- Renewable Resource Datasets

Grid Experimental Capabilities

- NREL Energy Systems Integration Facility
- Advanced Distribution Management System Testbed
- NREL Flatirons Campus
- Integrated Energy Systems at Scale (IESS) - Integrated multi-site integrated Power Hardware in the Loop Experiments

Energy Systems Integration Facility

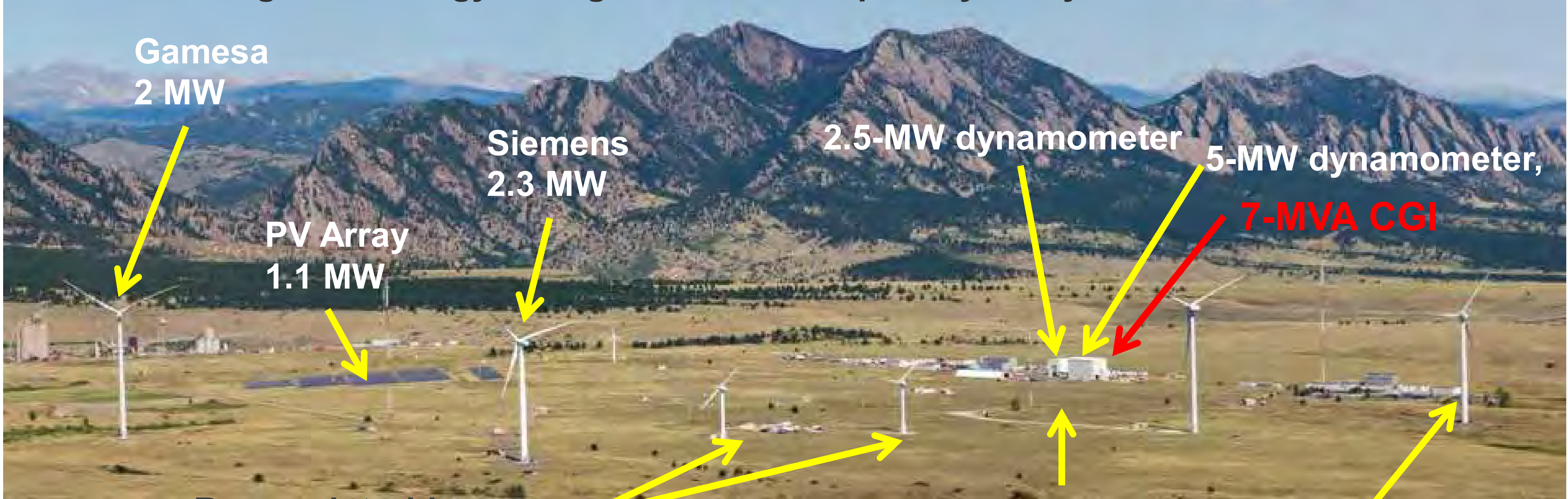
Shortening the time between innovation and practice

Unique capabilities:

- Multiple parallel AC and DC experimental busses (MW power level) with grid simulation and loads
- Flexible interconnection points for electricity, thermal, and fuels
- Medium-voltage (15-kV) microgrid area
- Virtual utility operations center and visualization rooms
- Smart grid lab for advanced communications and control
- Interconnectivity to external field sites for data feeds and model validation
- Petascale high-performance computing (HPC) and data management system in showcase energy-efficient data center
- MW-scale power hardware-in-the-loop simulation capability to evaluate grid scenarios with high penetrations of clean energy technologies.

Flatirons Campus

- **Total of 11 MW of variable renewable generation currently installed**
- **Many small wind turbines (less than 100 kW) are installed**
- **2.5-MW and 5-MW dynamometers**
- **7-MVA controllable grid interface (CGI) for grid integration experiments**
- **Multi-megawatt energy storage evaluation capability ready for use.**



Research Needs

Technology:

- Advanced functionality embedded in wind and PV inverters needs to **provide all grid services** and maintain stable grid operations (act like synchronous generators).
- Grid codes and standards are needed that enforce grid stability (updates to standards from the Institute of Electrical and Electronics Engineers and North American Electric Reliability Corporation)
- Need cost-effective energy storage methods (storage, flexible demand, power-to-gas).

Sensing, measurement, and forecasting:

- Improved solar, wind, and load forecasting
- Improved communications from measurements and data analytics to derive grid forecasts.

Power system operations and controls:

- Better algorithms and use of grid data to make decisions for power system operations and control
- Transmission and distribution energy management systems need to be able to control millions of distributed devices.

Power system design and studies:

- Need integrated transmission and distribution models to understand complexities and simulate both steady-state and dynamic conditions
- Need models that link electric power grid to other energy infrastructures
- Need models need to incorporate uncertainty and various market designs.

NREL Power Systems Engineering Center
www.nrel.gov/grid

NREL: Providing Solutions to Grid Integration Challenges

Thank You!